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THE MANUFACTURE AND EVALUATION OF BRAIDED
FIBRE REINFORCED COMPOSITE TUBES

M. SHELLEY

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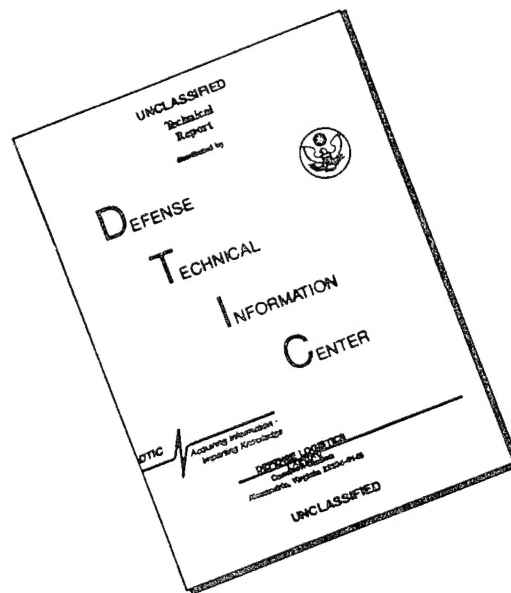
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THE MANUFACTURE AND EVALUATION OF
BRAIDED FIBRE REINFORCED COMPOSITE TUBES

by

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S U M M A R Y

The use of braiding for incorporating fibres into tubular structural elements made of reinforced plastics was investigated. A batch method of making multi-layered tubes with a controlled angle of fibre alignment (from layer to layer) is described. Details are given of a test method devised to evaluate the braided products.

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NOTATION

G	Modulus of rigidity
J	Polar moment of inertia
L	Gauge length
T	Applied torque
V_F	Fibre volume fraction
θ	Angle of twist

1 INTRODUCTION

Tubular structural elements have been successfully produced from composite materials by a variety of processes, such as pultrusion, wrapped cloth, filament winding, tape winding and wrapped pre-preg, and the qualities of the tubes so obtained are fairly well established.

Pultrusion, although best suited for production requirements, can only really produce longitudinally unidirectional fibre reinforcements. If torsional stiffness is required then some other process must be used. Filament winding is an obvious choice but the size of the winding apparatus may limit the product. Wrapped cloth and pre-preg can be beneficial but are not suited to continuous production.

Torsional stiffening fibres can, however, be laid down in a tubular structure by braiding at a point in a process, and the technique would be suitable for use in production. A braiding head was modified to produce multi-layered braided reinforced tubes and the effect of manufacturing parameters on the torsional stiffness of the products investigated.

2 METHOD OF MANUFACTURING TUBE

2.1 Equipment

A braiding head already exists that can satisfactorily handle heavily sized glass and carbon fibre, and unsized Kevlar fibre. This head was modified to control the rate of draw past the point of braiding and hence the resultant braid angle. This was defined as the angle subtended by the fibre (tangential to the tube surface) with respect to the axis of the tube. A variable speed drive was incorporated so that several different diameters of tube and angles of braid could be accommodated. This drove a rubber-surfaced vertically mounted capstan from the existing vertical handwheel shaft on the braiding head. The modified braiding head is shown in Fig 1.

2.2 Braiding Angle Determination

The range of speeds provided by the variable speed drive to the take-off capstan could not accommodate all the braiding angles envisaged. Different sized capstans were therefore used and the apparatus was recalibrated for each particular braid angle, the pitch being directly measured from the first braided layer on the mandrel. The angle was calculated using the measured pitch and the mean diameter of the first dry layer of reinforcement fibre placed on the mandrel which was measured at several points by micrometer. Since it was intended to produce tubes of the same bore, 9.53 mm (0.375 in), and nominal overall diameter 12.70 mm (0.50 in), the braid angle of the first layer would be easily determined.

Measuring subsequent layers was made difficult by the presence of the resin and the inherent softness of the uncured product during manufacture. Specimens were therefore prepared in which a number of layers were laid up at the approximately correct braid angle and excess resin removed, after which the product was cured and measured. The number of layers necessary for a given braid angle (Table 1) was determined and the increments required to maintain the correct braid angle between subsequent layers were calculated.

2.3 Batch Production of Specimen Tube and Impregnation of Successive Layers

A mandrel assembly was prepared, built up of four jointed mandrels, respectively Nos (1), (2), (3) and (4) on which the first layer of fibre was braided dry. When mandrel (3) was completely covered, the braiding head was stopped and the braiding bound with fine copper wire on either side of the screwed joint between mandrels (2) and (3). The dry fibre around the joint was then cut between bindings and mandrels (1) and (2) were unscrewed from mandrels (3) and (4), which were meanwhile suspended from a counterbalanced line. The take-off wire was returned by hand past the take-off capstan until the take-off wire could be hooked up to the top end of mandrel (3). Mandrels (1) and (2) (still screwed together) were removed to the bench and the braided fibres were impregnated with Araldite CY219 cold cure epoxy resin. The mandrels with the now wetted fibres were returned to the braiding head and the top end of mandrel (1) screwed on to the lower end of mandrel (4). By marking the top end of mandrel (1) with red dye, the start of the braiding cycle, the first layer, could be easily recognized. A mandrel joint is shown in Fig 2.

Braiding was then resumed until the joint between (1) and (2) was reached (Fig 3 shows dry fibre squeezing out the resin-rich under-layer). This process was repeated, taking off two mandrels at a time until the requisite number of layers had been acquired. As the braiding cycle passed each time, between mandrels (4) and (1), the take-off ratio was adjusted to allow for the increasing diameter of mandrel and braid at each pass.

2.4 Removing Excess Resin

After braiding and impregnation, the product had acquired a resin-rich outer layer (Fig 4). This was reduced by hanging the two pairs of mandrels from one end and wiping the surface using an extensible rubber orifice of about 70 per cent of the finished diameter of the product (see Fig 5). The section of rubber used in the first batch of specimens was 3 mm (0.125 in) thick by about 75 mm (3 in) square using an orifice of approximately 9 mm (0.35 in). Subsequent batches were wiped using a much thinner rubber sheet in an attempt to minimize fibre damage and misorientation on the outer surface. Some specimens (both unwiped and wiped) were subsequently wrapped in cellophane tape.

2.5 Removing Product from Mandrel

The ends of the parallel section of braided fibre on each pair of mandrels, and the braided fibre joins between pairs of mandrels were carefully sawn through. The products were then stripped from the mandrels using a split die of 9.52 mm (0.375 in) bore as an end stop and a length of rod bearing on the small end of the mandrel. After removing from the mandrel, the products were suspended from one end and post-cured at room temperature for at least 4 days.

2.6 Preparing Specimens for Test

Square ends were cast-on the test specimens to permit torsion testing in an Avery 113 N m (1000 in lbf) torsion test machine.

The sawn-off end of each specimen was dressed for squareness and freed of rag. Each specimen was cut to a length of 160 mm (6.3 in) and cleaned before casting the ends in a multi-aperture mould (Fig 6). The mould was made from Stubbs steel of 12.7 mm (0.5 in) square section cut to lengths of 32 and 50 mm (1.25 and 2.0 in) and two plates 12.7 mm (0.5 in) thick and 50 mm (2.0 in) high. The individual parts were separately waxed and polished before being assembled as shown. The parallel side plates were clamped together to prevent resin seepage along the joint faces of the assembly.

Approximately 1.5 ml of CY 219 resin, filled with 30 per cent of Armospheres (to enhance the compressive strength of the cast resin), was then injected into each cavity of the mould, using a large hypodermic syringe; this completely filled the cavity when one end of the tube was inserted to the appropriate depth so that a slight meniscus was formed between the resin and tube, providing a smooth transition from square to tubular section.

After one end of each specimen had been inserted, the resin was cured for 3 to 4 hours- then the side plates were unclamped and the mould dismantled. The component parts were cleaned, separately waxed, polished and re-assembled as before. A small air hole was drilled axially through each of the cast ends and the specimens were inverted to cast the opposite end. After curing, the tooling was again dismantled. Both cast ends on each specimen were deflashed and flats were machined on their corners to accommodate the specimen in the NEL twist angle gauge. The specimens were allowed to post cure at room temperature for at least three days to effect full hardening of the cast ends. The final form of specimen is shown in Fig 7.

3 TEST METHOD

In a study of torsional stiffness of carbon fibre composites, ⁽¹⁾ a test method was devised using a torsion load cell and a rotating potentiometer to plot continuously torsion load and angle of twist during the test. This twist monitoring device was not sensitive enough for the torsionally stiff braided tubes. A new method of measurement was therefore conceived (Fig 8) using an NEL radial optical grating and

reading head, attached to opposite sides of a pair of concentric aluminium alloy tubes. The advantages of this device were:-

- a. long gauge length of 100 mm (4 in) giving good sensitivity;
- b. digital electronics, which are intrinsically noise-free; and
- c. rapid clamping and unclamping from the specimen, making it suitable for fast testing (previously⁽¹⁾ accurate bonding of reference discs to the specimen was required.)

The twist gauge was energized and monitored by an integrated unit including a power supply, a binary up/down counter and logic unit which counts pulses representing 0.1° of notation; this digital information is exhibited on a four digit display and is then digital-to-analogue converted in the range 0 - 10V before being fed to an output socket coupled to the X axis of an X-Y plotter.

Torsional moment was measured by a tubular steel torsion load cell manufactured from En26 steel. It incorporates a tapered keyed portion to match the torsion rig and a 19 mm (0.75)in A.F. square socket to match the specimen adaptor on the test machine.

The load cell was gauged with a full bridge of 120 Ω foil strain gauges and the signal was amplified by means of a strain gauge amplifier feeding the X-Y plotter directly in the y axis. The complete test apparatus is shown in Fig 9.

The specimens were fitted in turn to the NEL twist angle gauge and into the square adaptors of the torsion test machine. Torsion was applied at a constant rate of 170° per minute, which was the slowest speed that the torsion machine would maintain satisfactorily. The tests continued until either the specimen or its cast ends failed. Fig 10 shows a typical test chart as plotted by the apparatus described. Although these results show, as expected, some non-linearity, the relationship up to about 10° was sufficiently linear to allow the use of a linear formula.

4 PARAMETERS IN THE DETERMINATION OF SHEAR MODULUS

4.1 Theoretical Formula

The elastic shear modulus is given by

$$G_{12} = \frac{T}{\theta} \times \frac{L}{J}$$

where G = modulus of rigidity

T = applied torque

θ = angle of twist

L = gauge length

J = polar moment of inertia

J was derived from specimen dimensions and its measurement posed some problems.

4.2 Specimen Measurement

The inherent roughness of the outer surface of the braided tubular specimen made it difficult to measure the outside diameter accurately. After some experiments, a probe was developed which enabled a Talysond surface profile measuring machine to track satisfactorily round the profile of the braided surface. The 'best fit' circle was then superimposed on the profile record and the mean height of all peaks and troughs was established, to give an approximate value for the 'minimum continuous circle' that could be superimposed on the section. This was done for each of four transverse sections on a sample of each representative braiding angle, and this minimum continuous circle used as the overall diameter in calculating the polar moment of inertia.

4.3 Fibre Volume Fraction Determination

Small coupons were removed from each specimen and the fibre volume fraction was estimated by a 'burn-off' test. As expected from a geometric evaluation, the fibre volume fraction increased with

increasing braid angle. To provide direct comparisons between specimens, the shear modulus was modified to allow for the differences in volume fraction. The factor used was derived from the graph shown as Fig 11, which represents the band of theoretical prediction⁽²⁻⁷⁾ for the relationship between fibre volume fraction and longitudinal shear modulus. All the theoretical predictions fall within fairly close limits up to volume fractions of about 55 per cent; beyond this level, predicted values differ significantly. A micrograph of a typical transverse section is shown in Fig 12.

5 RESULTS

The mean results of tests on four specimens of each braid angle are presented in Table II. The corrected values correlate fairly well with the results of torsion tests on filament-wound glass-epoxy tubes obtained by Wall & Card⁽⁸⁾ (Fig 13). Most specimens failed by initial compressive de-bonding of the poorly aligned surface fibres, followed by shear failure parallel to the filaments loaded in tension. However, although tests on specimens having a nominal 45° braid angle terminated in shear failure of the cast end fittings, the torque at failure was high enough to allow calculation of the shear modulus as with the other specimens.

The results show the expected dependance of shear modulus on braid angle. Owing to the geometry of the process itself, braiding at significantly less than 30° braid angle or significantly more than 70° is not yet practical.

6 RECOMMENDATIONS

Braiding would thus seem ideal for continuous production of torsionally stiff tubular elements and for use in overlaying pultruded fibre products. The process both circumferentially compacts the product and adds torsional stiffness to pultruded products.

It is intended to evaluate both carbon fibre and Kevlar as alternative reinforcing fibres and to investigate the design and manufacture of hybrid configuration tubes.

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- 12 Photomicrograph of typical transverse section through specimen
- 13 Comparison between filament-wound and braided glass-epoxy tubes.

TABLE 1**Braid Angle and Layer Configuration**

Braid Angle	Lead of inner layer (9.53 mm) (mm)	Lead of outer layer (12.70 mm) (mm)	No of layers
30°	52	69	10
40°	36	48	9
45°	30	40	8
50°	25	33	7
60°	17	23	6
70°	11	15	5

Table 2

Mean Results

Braiding angle		Fibre volume fraction (per cent)	Inside diameter (mm)	Corrected outside diameter (mm)	Polar moment of inertia ($\text{m}^4 \times 10^{-9}$)	Reference angle of twist (θ_T) (rad/10)	Torque at θ_T (N m)	Gauge length (cm)	Shear modulus (GN/m ²)	Corrected shear modulus* (GN/m ²)
Nominal (degrees)	Actual (degrees)									
30	29.4	44.4	9.53	12.55	1.6272	1.7453	28.59	10.16	10.23	11.8
40	43.2	51.0	9.53	12.40	1.5129	1.7453	39.80	10.16	15.31	15.0
45	46.7	50.2	9.53	12.40	1.5129	1.7453	41.35	10.16	15.91	15.9
60	61.0	53.4	9.53	12.34	1.4684	1.7453	33.08	10.16	13.11	12.2
70	67.0	55.0	9.53	12.95	1.9528	1.7453	32.54	10.16	9.70	8.5

*Shear modulus corrected for 50 per cent volume fraction

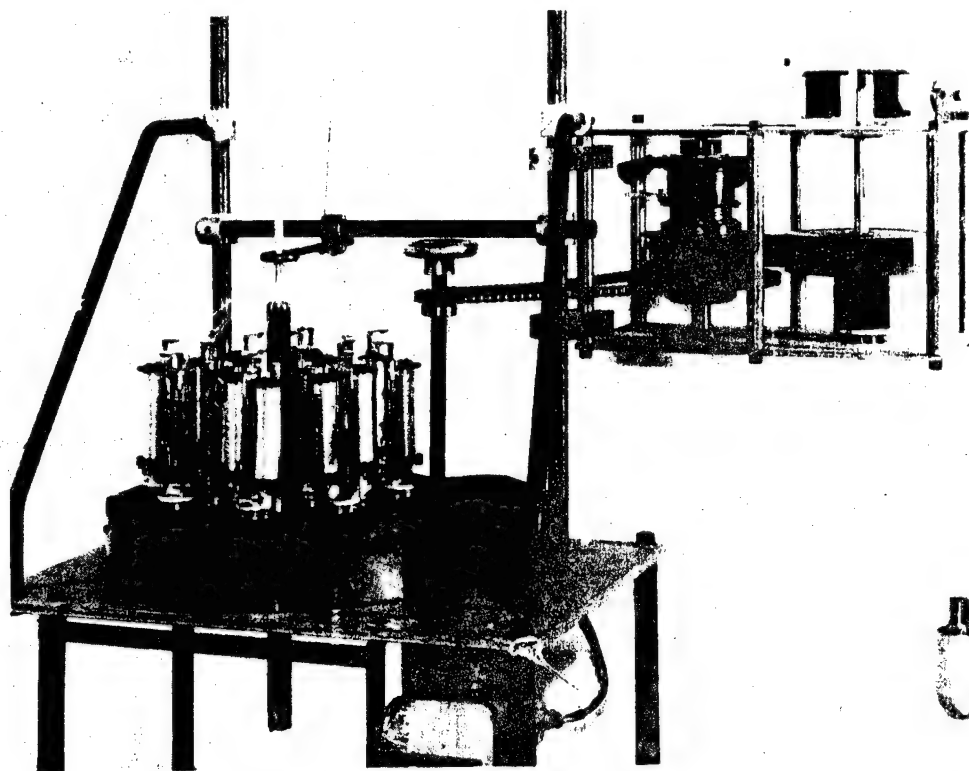


Fig. 1 Modified Braiding Head

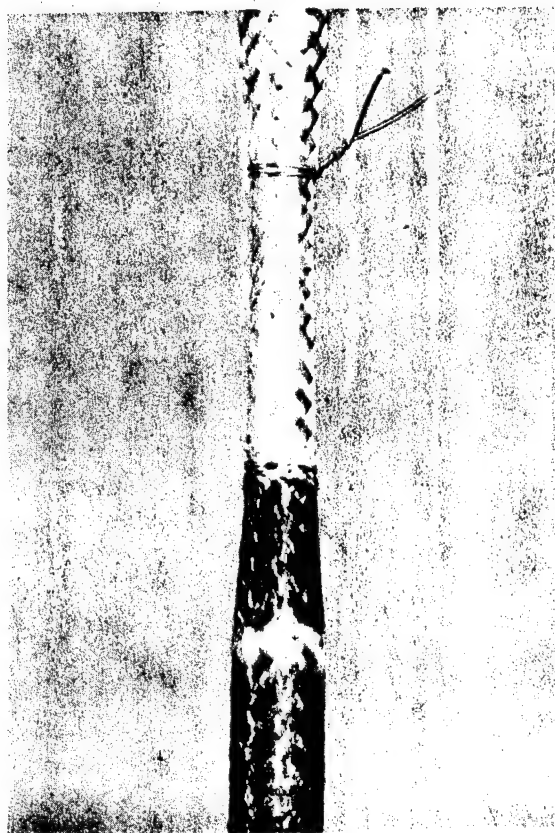


Fig. 2 Typical Mandrel Joint Before Cutting of Dry Fibres

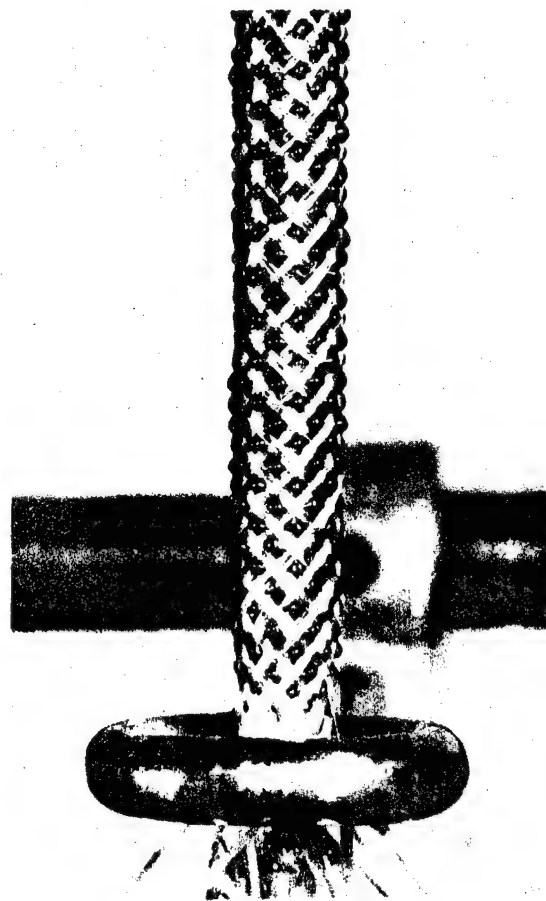


Fig. 3 Dry Fibre Squeezing Excess Resin From Impregnated Under Layer

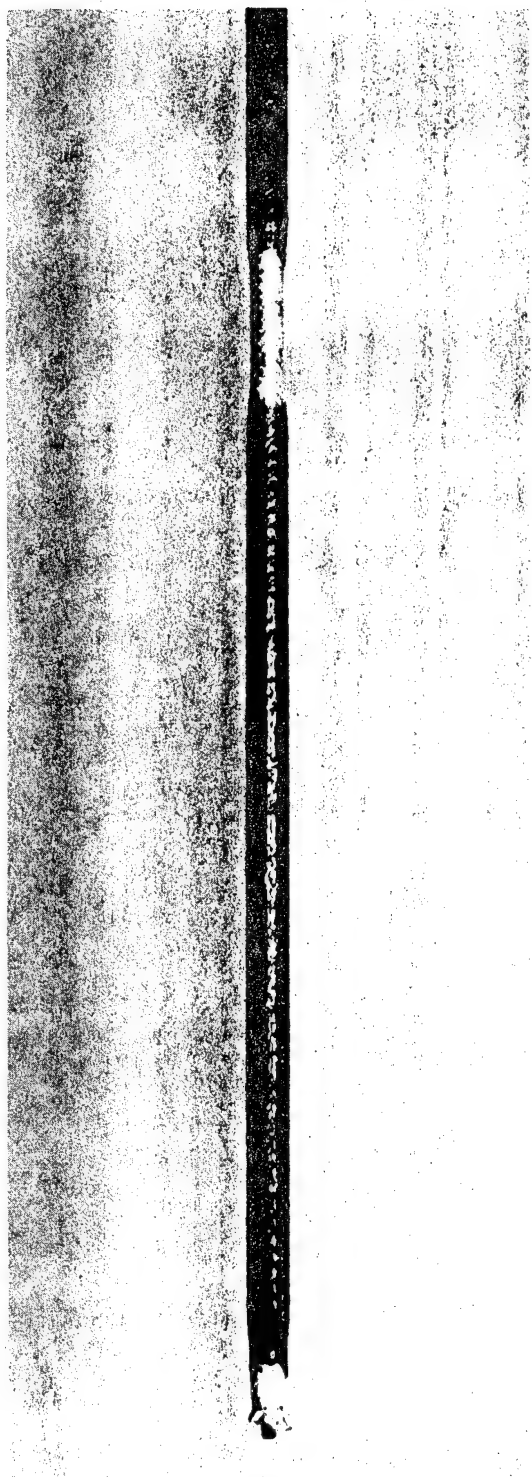


Fig. 4 Finished Tube on Mandrel Before
Wiping Excess Resin



Fig. 5 Finished Wiped Tube

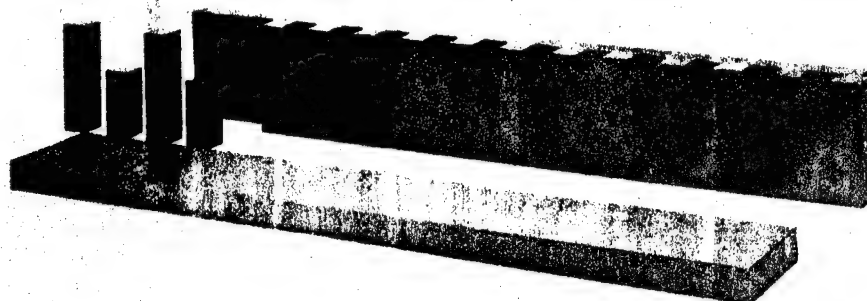


Fig. 6 Multi-Aperture Mould For Casting Ends on Specimens

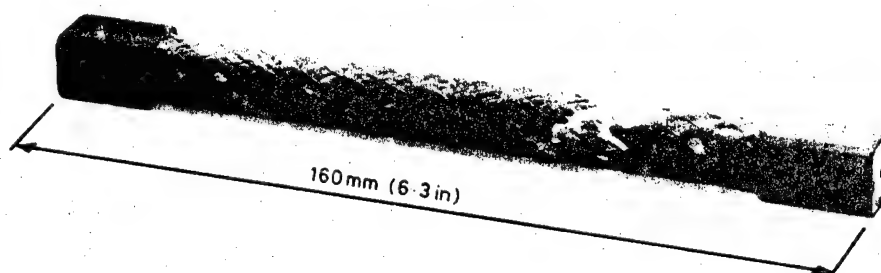


Fig. 7 Specimen

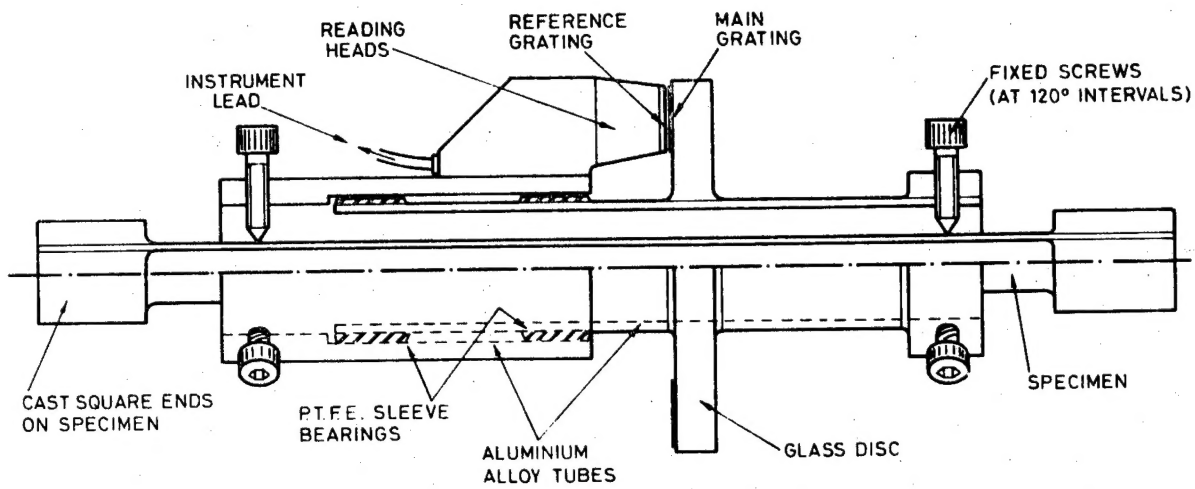


Fig. 8 NEL Twist Angle Gauge

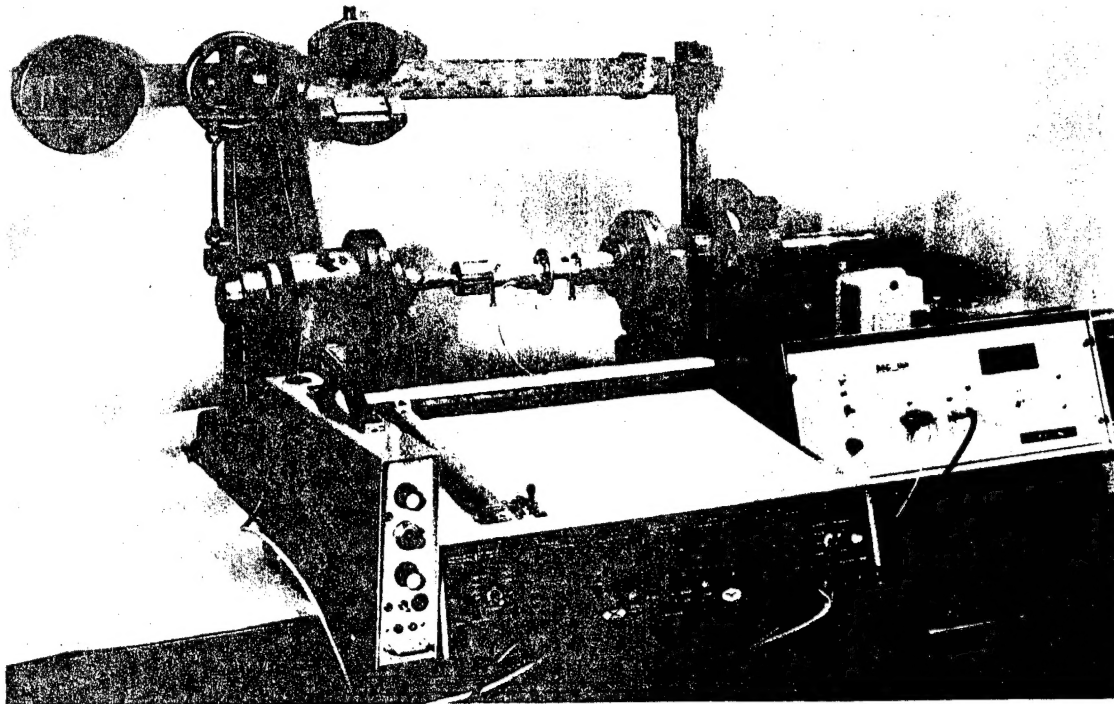


Fig. 9 General View of Test Apparatus

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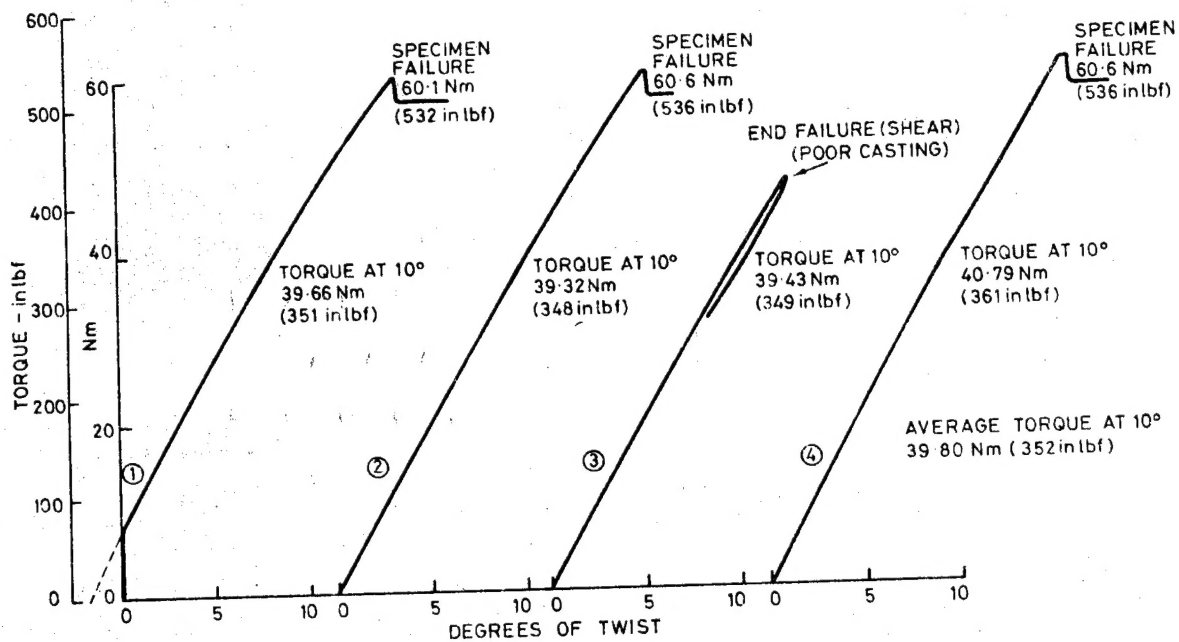


Fig. 10 Typical Test Results

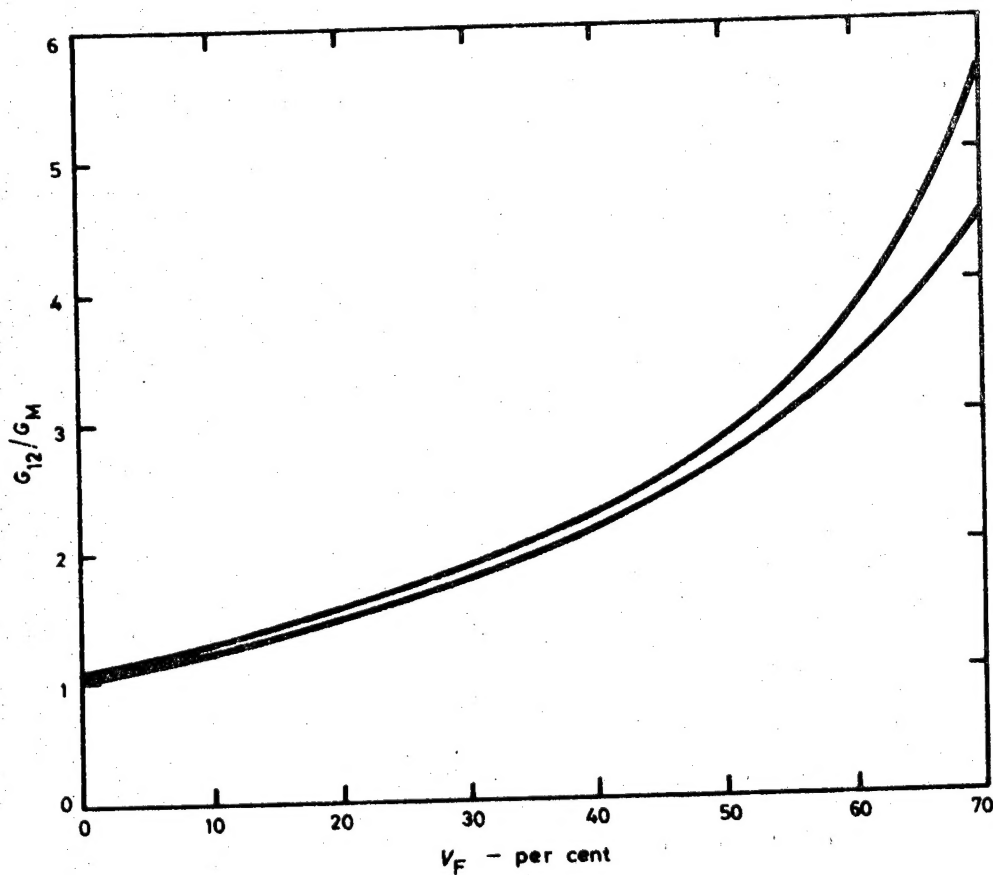


Fig. 11 Theoretical Predictions of Longitudinal Shear Modulus



Fig. 12 Photomicrograph of Typical Transverse Section of Specimen

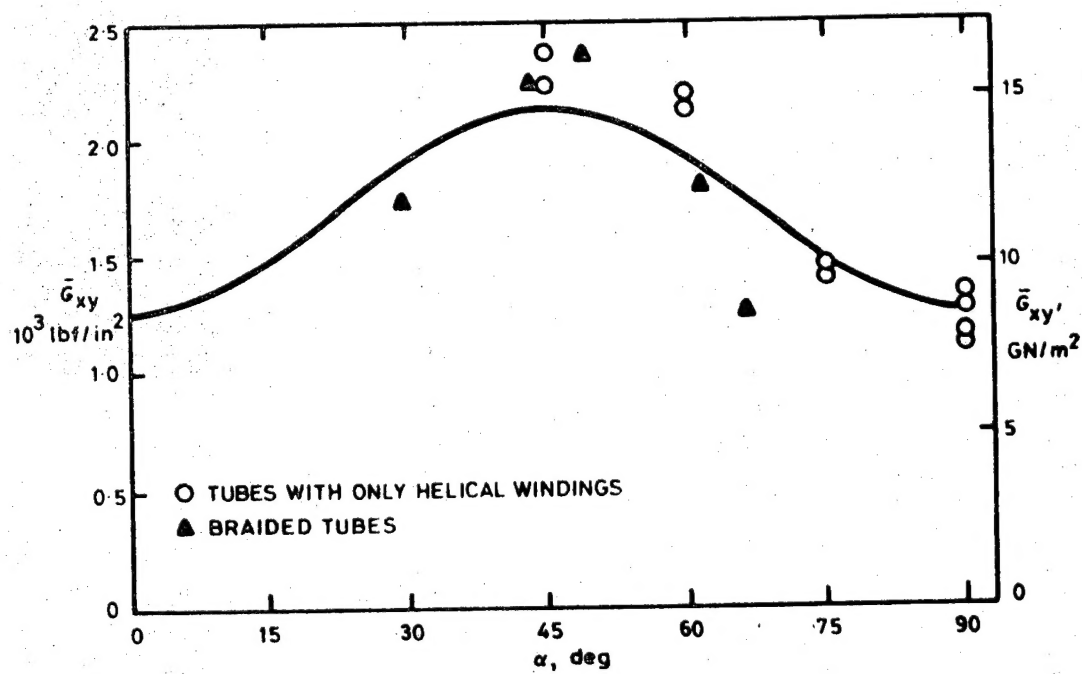


Fig. 13 Comparison Between Filament-Wound and Braided Glass-Epoxy Tubes

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